



# CC0pi results from T2K

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NuFact 15 – Rio de Janeiro

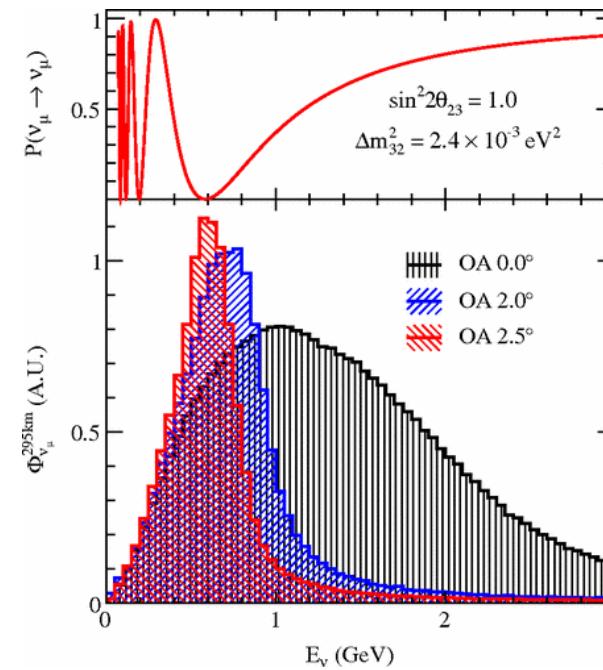
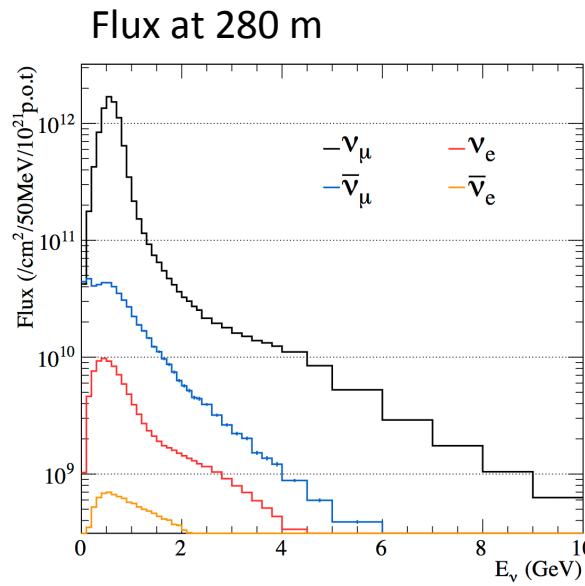
# The T2K experiment

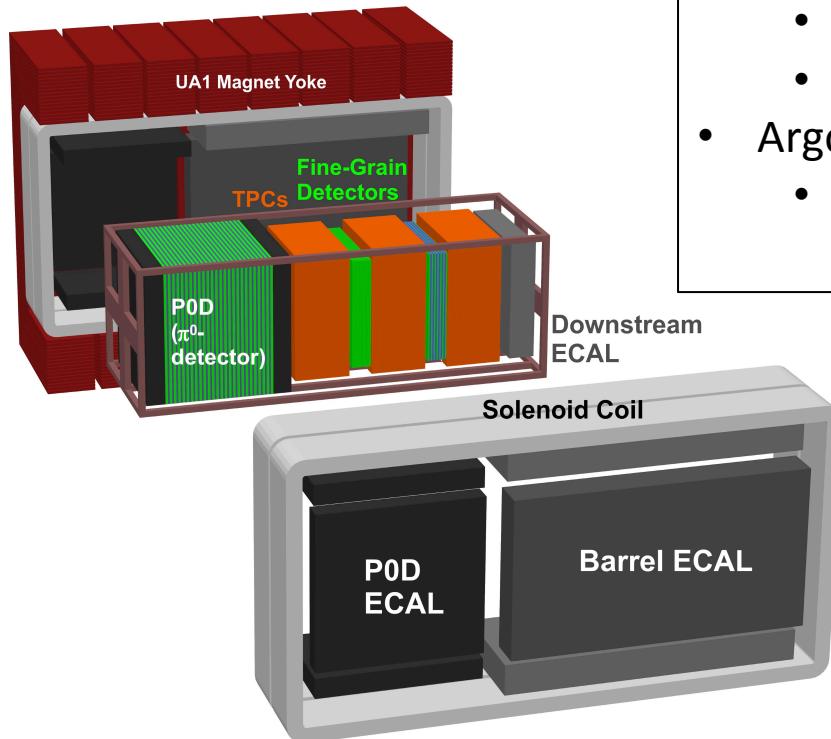


- Long-baseline neutrino oscillation experiment in Japan
- Runs from J-PARC in Tokai, to Super-Kamiokande
- Primary goal to search for  $\nu_\mu \rightarrow \nu_e$  oscillations

# T2K flux prediction

- T2K uses an off-axis  $\nu_\mu$  beam
  - Flux tightly peaked at 0.6 GeV to match oscillation peak
- Simulation based on FLUKA/GEANT3
- Hadron production predictions from measurements at NA61/SHINE at CERN

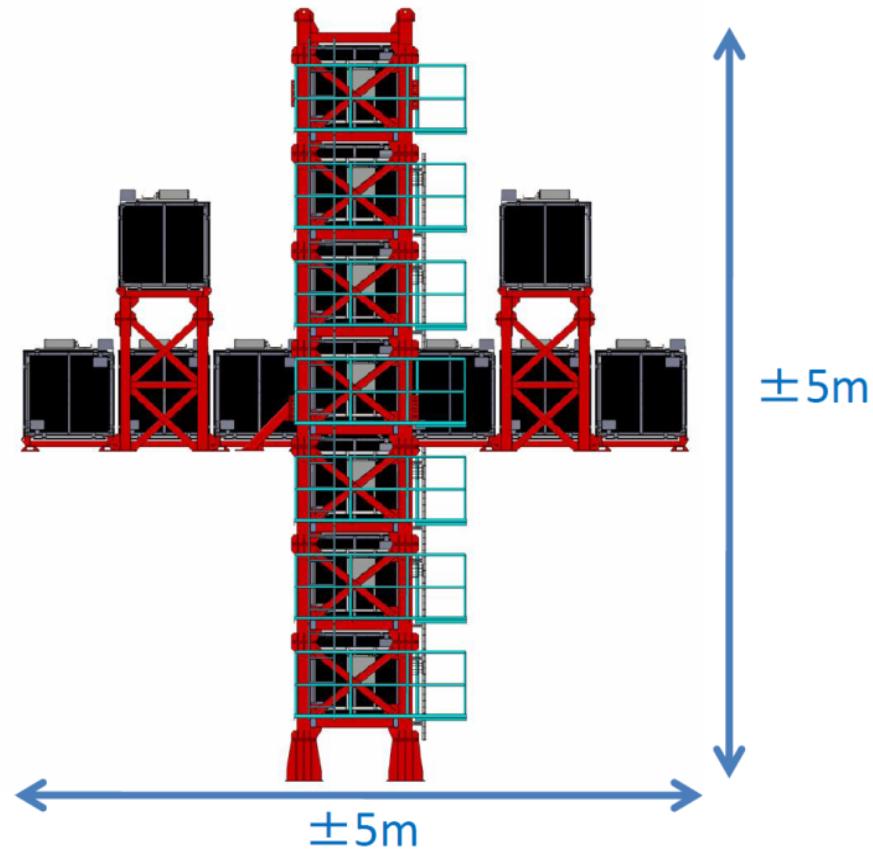




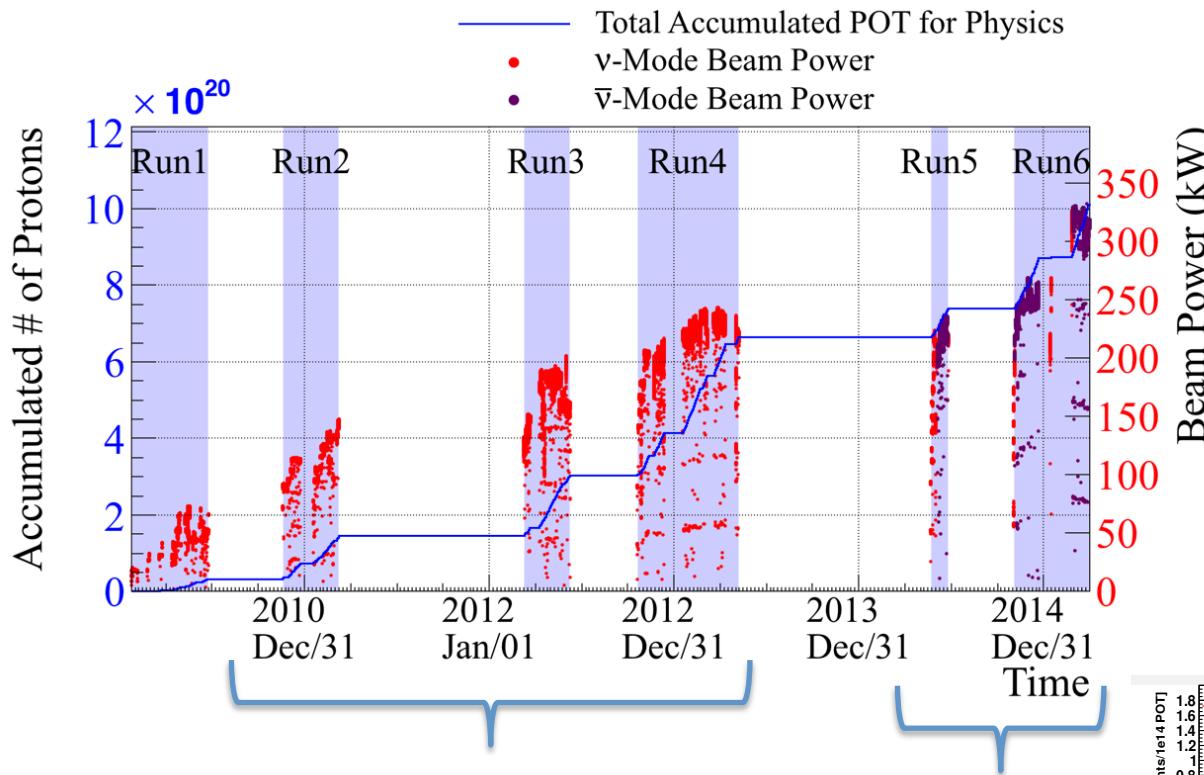
- Fine-grained **scintillator target (FGD1)**
  - Provides vertex resolution
  - 1 cm x 1 cm bars
- Argon gas **TPCs** in 0.2 T **magnet**
  - Provides tracking, momentum, charge ID, and PID

- Other features (not used here):
  - Water layers in FGD2
  - Pi-zero detector (P0D)
  - Also contains water layers
  - ECal
  - Side muon detectors

- On-axis near detector
- Layers of iron and scintillator
- Designed primarily to monitor beam direction and rate
- Also being used for cross section measurements



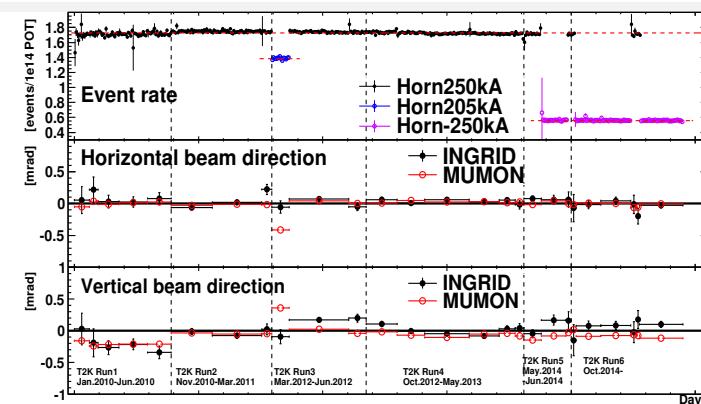
# Data taking periods



Data used for CCQE-like measurements at ND280

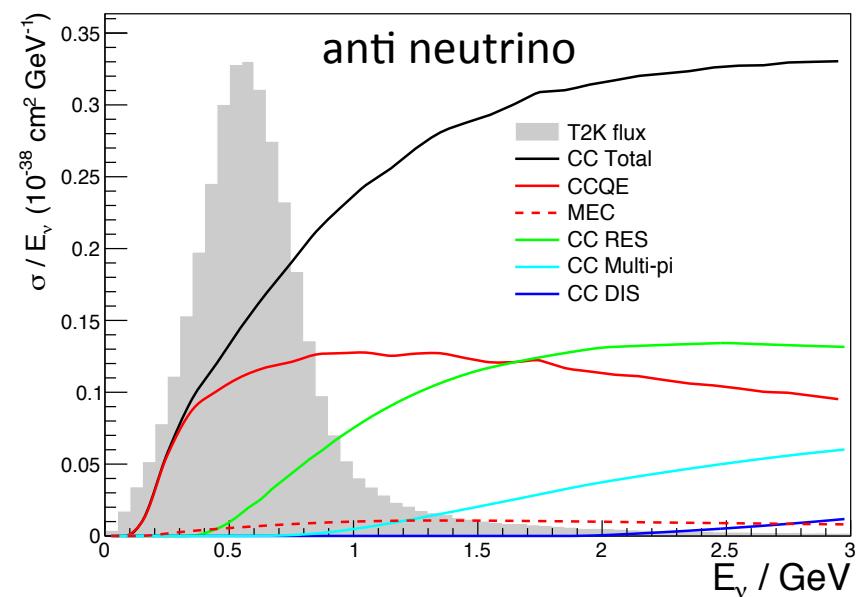
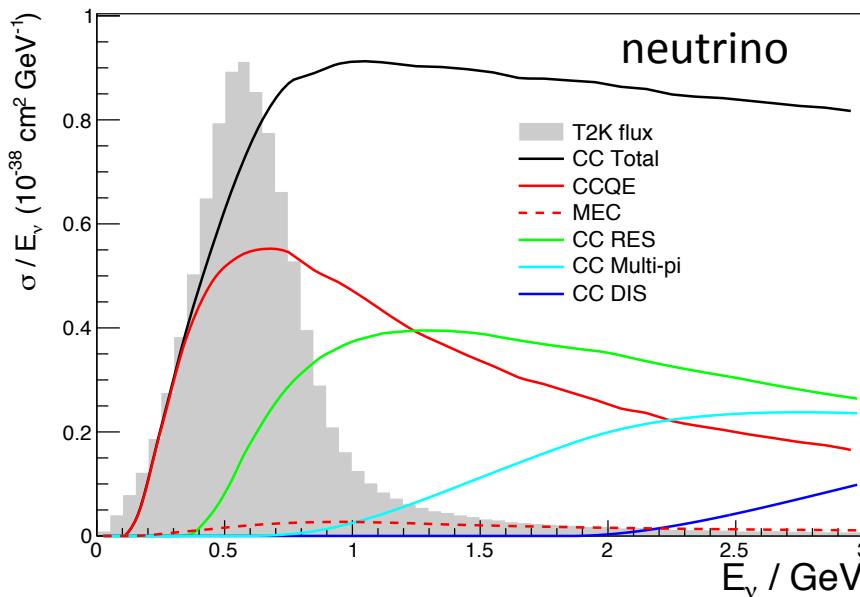
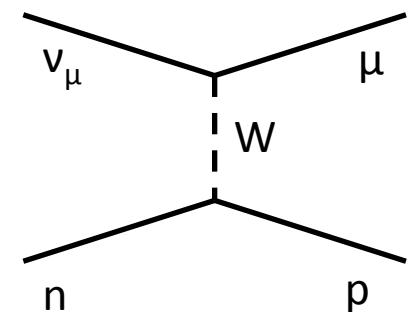
Antineutrino mode data

- T2K runs 2-4 used in this analysis
- 5.73E20 POT
- Beam direction and rate very stable



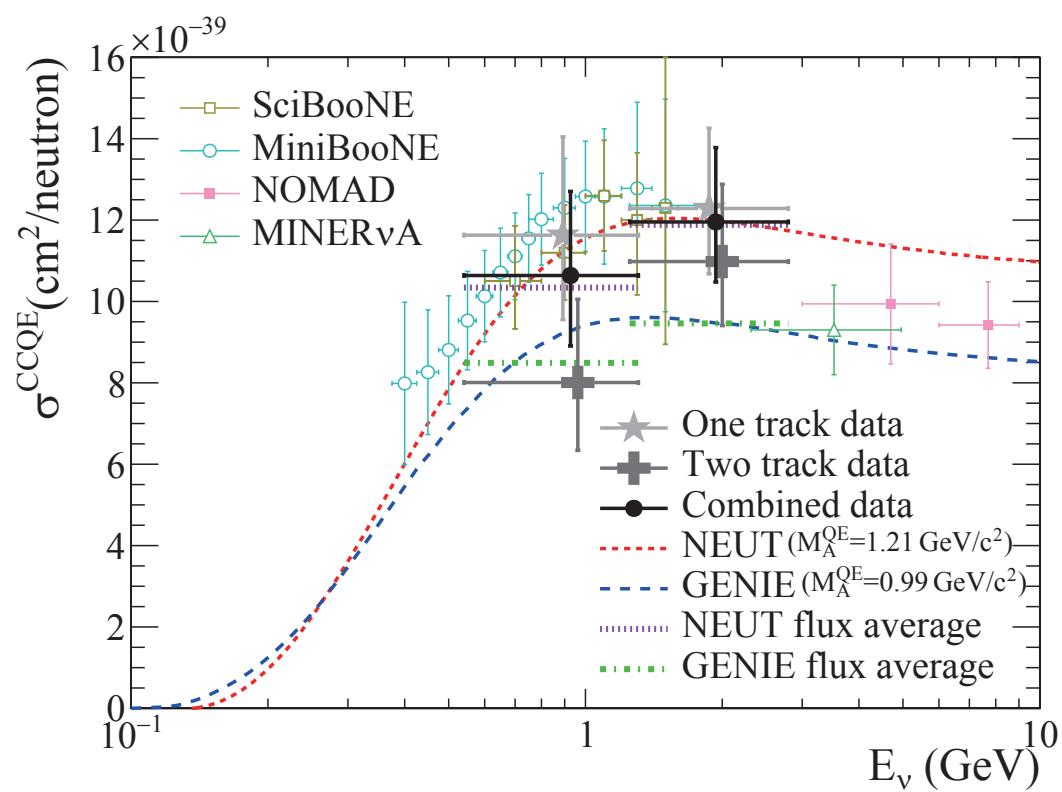
# Interactions at T2K

- CCQE is by far the dominant interaction at T2K energies
  - 80% of CC events at off-axis flux peak
- CCQE assumption used to estimate neutrino energy for oscillation analysis



# On-axis CCQE

- INGRID used to measure CCQE cross section with on-axis flux (peak 1.5 GeV)
- 2 bin measurement in neutrino energy
- Kinematic cuts used to enhance CCQE purity
- Sample split into 1- and 2-track samples
- Large amount of model dependence seen, and tension between 1- and 2-track samples
- Perhaps kinematic cuts not well-understood?





# Off-axis CCQE-like strategy

- Understanding CCQE-like interactions is critical for T2K
- Measurement needs to be model-independent
  - Flux integrated cross section measured
  - As a function of **measured variables** (muon kinematics)
    - No dependence on model to translate to  $E_\nu$  or  $Q^2$
  - Topology-defined signal (**CC0pi**)
    - No dependence on FSI model
- **Two separate analyses**, different approaches, serve as checks of each other's model-dependence
- For the measurement presented here, FGD1 is used as the target (CH)



# Selections

- Data quality

- Every ND280 subdetector must be functioning correctly
- Beam spill must be reported as good



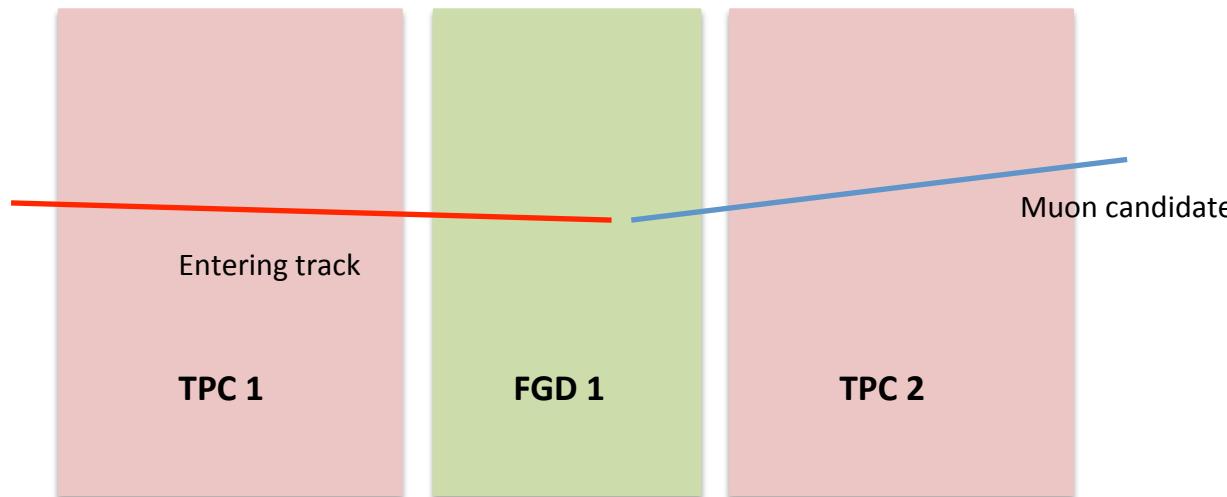
# Selections

- Data quality
- Highest momentum negative track selection
- Starts in FGD fiducial volume
  - Muon candidate defined as highest momentum negative track
  - Must have at least 18 TPC hits for reliable momentum and PID measurements

# Selections

- Data quality
- Highest momentum negative track selection
- Starts in FGD Fiducial volume
- Broken track cut

- Events where track starts in final 2 layers of FGD1 cannot have another track ending in the FDG FV





# Selections

- Data quality
- Highest momentum negative track selection
- Starts in FGD Fiducial volume
- Broken track cut
- Muon PID
  - $dE / dx$  measurements in TPC distinguish between muons and electrons with high efficiency

# Selections

- Data quality
- Highest momentum negative track selection
- Starts in FGD Fiducial volume
- Broken track cut
- Muon PID

## Analysis I

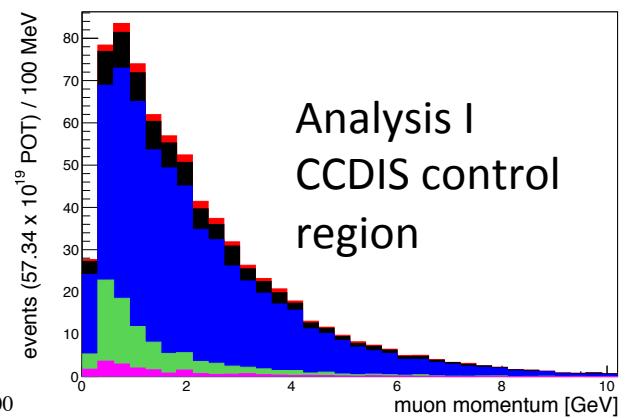
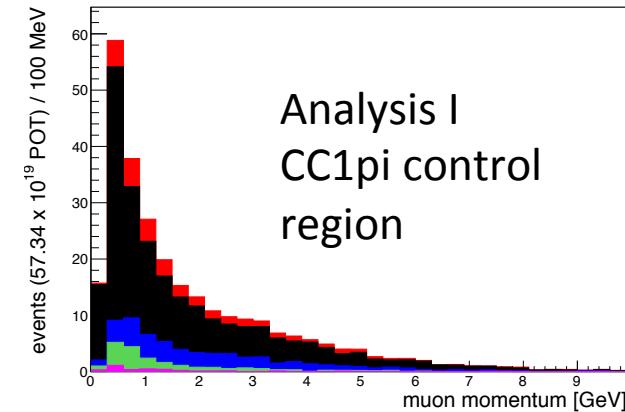
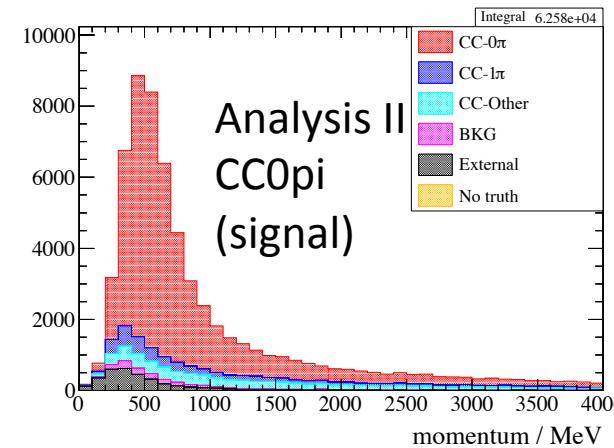
- Proton topologies
  - Muon-only
  - Muon + TPC proton
  - Muon + FGD proton
  - TPC proton + FGD muon
- No dependence on pion rejection
- Additional high-angle tracks
- High purity

## Analysis II

- Pion rejection:
  - Pion-like TPC tracks
  - Pion-like FGD-only tracks
  - Michel electron (delayed)
  - Electron-like TPC tracks (due to  $\pi^0$  decay)
- Fully proton-inclusive
- Higher efficiency

# Backgrounds

- Dominant backgrounds are:
  - CC1pi with missed pion (low momentum or high angle)
  - CC  $\pi^0$  where photons do not convert
  - External interactions in magnet (high angle)
- Analysis I uses 2 background-specific selections as constraints (CC1pi, CCDIS)
- Analysis II uses external data constraints on background models



## Analysis I

- Likelihood fit
- Simultaneously fit **background model parameters** and bin-by-bin signal cross sections

$$N_j = \sum_i^{true\ bins} \left[ c_i \left( N_i^{MC\ CC0\pi} \prod_a^{model} w(a)_{ij}^{CC0\pi} \right) + \sum_k^{bkg\ reactions} N_i^{MC\ bkg\ k} \prod_a^{model} w(a)_{ij}^k \right] t_{ij}^{det} r_j^{det}$$

- Minimise  $\chi^2$

$$\chi^2 = \chi_{stat}^2 + \chi_{syst}^2 = \sum_j^{reco\ bins} 2(N_j - N_j^{obs} + N_j^{obs} \ln \frac{N_j^{obs}}{N_j}) + \chi_{syst}^2,$$

## Analysis II

- Bayesian unfolding
- Extract **smearing matrix** from MC
- Use **prior prediction** to calculate **unsmearing matrix**
- Apply to data to reveal **posterior prediction**

$$P(t_j|r_i) = \frac{P(r_i|t_j)P(t_j)}{P(r_i)}$$

$$N_{t_j}^{unfolded} = \frac{1}{\epsilon_j} \sum_i P(t_j|r_i)(N_{r_i} - B_{r_i})$$

Background prediction

# Uncertainties

## Flux

- ~10% normalisation uncertainty
- Shape uncertainty small, and has negligible effect on measurement
- Constrained by measurements at NA61/SHINE
- In-situ T2K beam measurements too

## Cross section + FSI

- NEUT used as default model
- Model parameter uncertainties estimated from comparisons to external data
- Some empirical parameters, normalisations

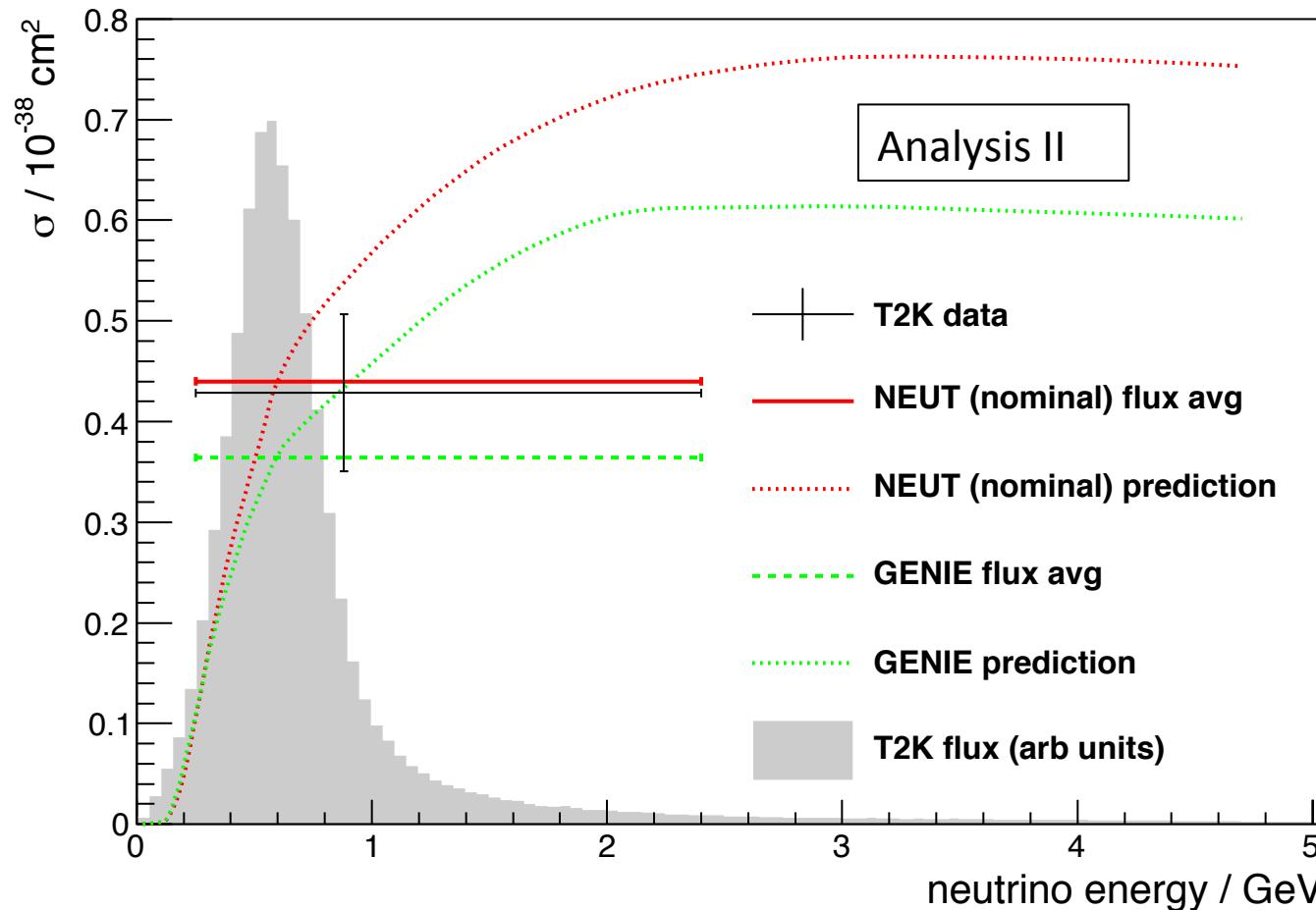
## Detector

- Vary underlying parameters, such as magnetic field strength
- Most have a small effect (<1%)
- Near phase space edges effects become larger
- Analysis II suffers from large pion re-interaction uncertainties

## Results

- Dominant uncertainty is **flux normalisation ~10%**
- Shape errors enter primarily from statistics and background uncertainties
- Vary between analyses and bins, around **1-5%**

# Results – integrated xsec



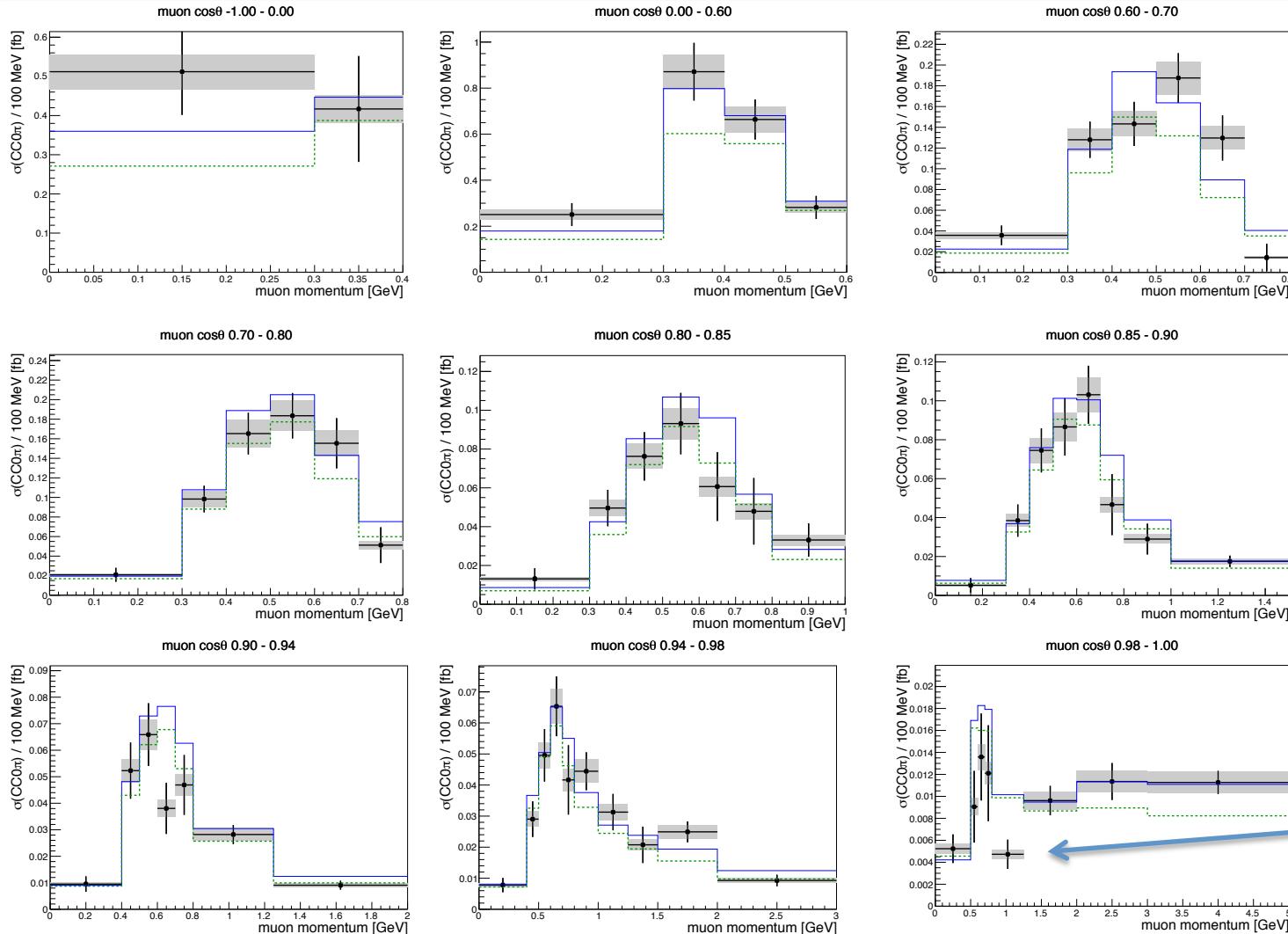
Two analyses agree to within statistical uncertainty

Result is in agreement with both NEUT and GENIE predictions

NEUT – v5.1.4.2  
GENIE – v2.8.6

Both predictions based on RFG model NEUT  $M_A = 1.21 \text{ GeV}$ , GENIE  $M_A = 0.99 \text{ GeV}$

# Differential results



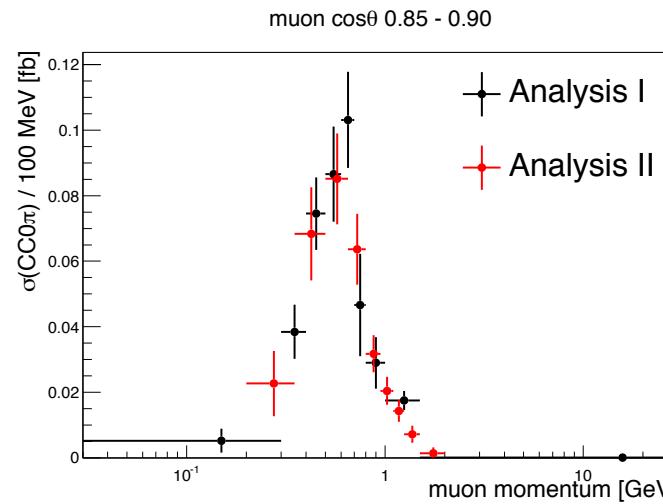
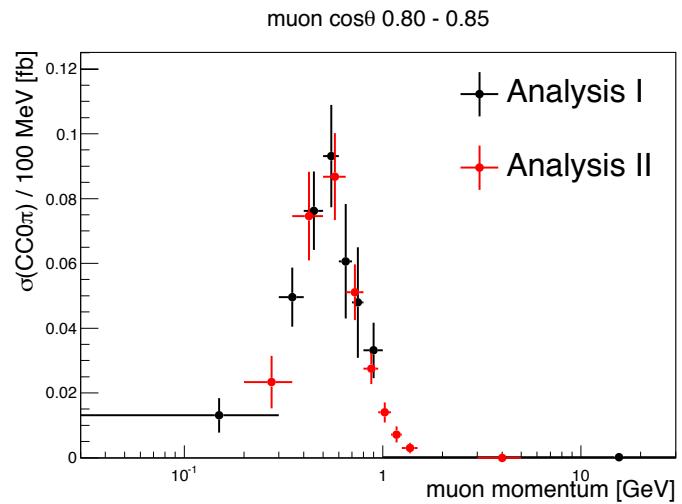
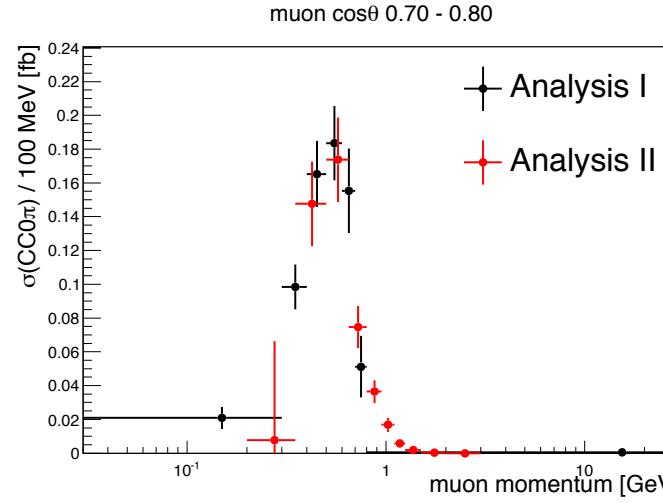
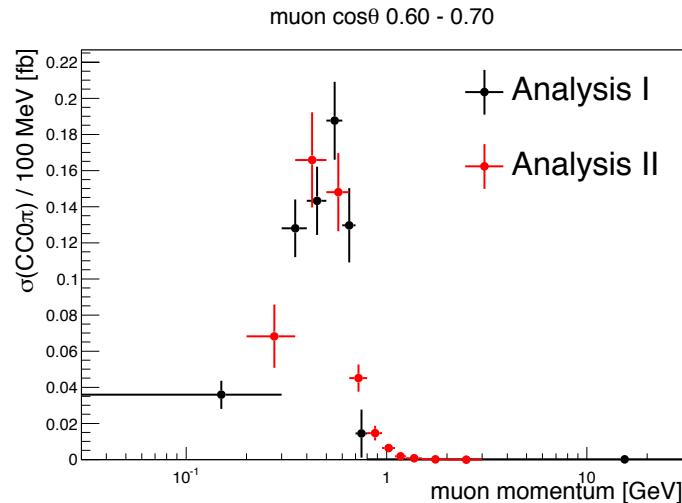
**Analysis I**

-----	NEUT
- - -	GENIE

Norm error  
+ Shape error

This “dip” is seen in both analyses and not predicted by models

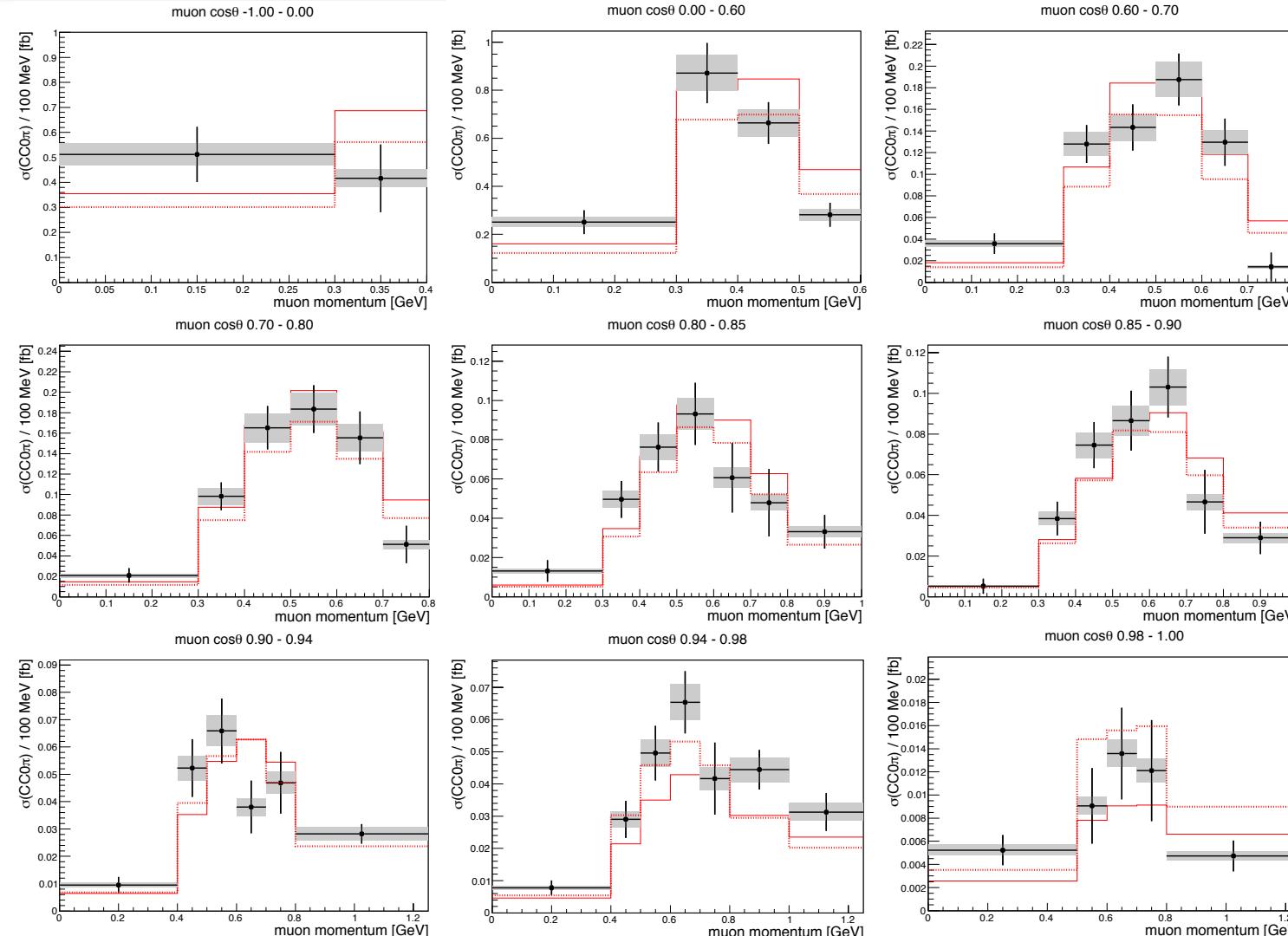
# Analysis comparison



Almost perfect agreement between the analyses despite using different binnings, background treatments, cross section extraction methods, etc

Gives a high degree of confidence in the model-independence of our results

# New models



## Analysis I

- Norm error
- Shape error
- Martini model
- Nieves model

Compare results to two “new” models, including 2p2h components

Models only considered valid up to 1.2 GeV

# Conclusions

- T2K has begun measuring exclusive topology cross sections
  - CC0pi presented in this talk
  - See talk by M. Nirkko for CC1pi
- Some interesting features are visible compared to generator/theory predictions in the CC0pi measurement



# The future

- Expanded phase space
  - Higher angle tracks
  - Backwards tracks
- Proton information
  - Separate proton topologies
- Antineutrinos, water targets, ratios...